**EARLY AND LATE CHONDRULE FORMATION: NEW CONSTRAINTS FOR SOLAR NEBULA CHRONOLOGY FROM $^{26}Al/^{27}Al$ IN UNEQUILIBRATED ORDINARY CHONDRITES:** S. S. Russell[1], G. R. Huss[2], G. J. MacPherson[1], and G. J. Wasserburg[2]. [1]Dept. Min. Sci., NHB-119, National Museum of Natural History, Smithsonian Institution, Washington DC 20560, USA. [2]Lunatic Asylum, Div. of Geol. and Planet. Sci., 170-25, Caltech, Pasadena, CA 91125, USA.

As part of our continuing effort [1,2] to better constrain the distribution and abundance of $^{26}Al$ in the early Solar System, we have identified and measured Mg-Al isotopic systematics in 2 new CAIs and 4 new Al-rich chondrules from the unequilibrated ordinary chondrites (UOCs), Semarkona (LL3.0), Moorabie (L3.4), and Chainpur (LL3.4). All of the chondrules contain either clear, isotropic, Al-rich glass or calcic plagioclase that is clearly of igneous, not metamorphic, origin.

**CAIs:** Semarkona 4128-3-1 is a ~390×180 µm, irregularly-shaped Type A inclusion. The interior is a dense, polygonal-granular intergrowth of equant melilite crystals ($Åk_{7-15}$; ≤30 µm) that enclose tiny grains of spinel (≤5 µm) and less abundant perovskite (≤2 µm). Much of the contorted outer surface is rimmed by a 2-4 µm layer of aluminous diopside, suggesting that this CAI was never much larger than it now is. In the outer parts of the CAI, melilite is corroded and embayed by secondary sodalite. Moorabie 6302-2-1 is a compact elliptical CAI, ~150×275 µm, consisting of a fine-grained, dense intergrowth of hibonite blades (≤40 µm; 0.6-4 wt % MgO, 0.7-7% $TiO_2$, 1-6% FeO) enclosed in ragged spinel (12-14% FeO, 1-5% $Cr_2O_3$), rounded and equant ilmenite grains (~5 µm) enclosed in both spinel and hibonite, and an interstitial intergrowth of sodalite and (?) phyllosilicate that embays and apparently replaces spinel. Spinel and hibonite crystals show slight compositional zoning, with FeO and $Cr_2O_3$ more enriched on the outside of crystals and along fractures. The shapes of the ilmenite crystals indicate that they might formerly have been perovskite. Both CAIs contain clear excesses of radiogenic $^{26}Mg$ ($^{26}Mg^*$) (Table 1) with initial ratios (($^{26}Al/^{27}Al)_o$) indistinguishable from the canonical value for CAIs from carbonaceous chondrites. Secondary sodalite in Semarkona 4128-3-1 also contains $^{26}Mg^*$ and gives the same $(^{26}Al/^{27}Al)_o$ as the primary minerals.

**Chondrules:** Semarkona 4128-3-2 is a lens-shaped chondrule fragment, 370×320 µm, with a coarse barred-olivine structure. Interstitial to the olivine ($Fo_{99-100}$) are ~40×10 µm laths of untwinned plagioclase ($An_{84-93}$), and interstitial to these in turn are small grains of aluminous diopside and minor $SiO_2$-rich glass. Near the center of the chondrule is a single, 50 µm, rounded, clear, spinel crystal ($Cr_2O_3$ 0.5-0.7%; FeO 0.3%). The igneous Crystallization Sequence (*CS*) is: spinel, olivine, anorthite, pyroxene, glass. Chainpur 1251-16-2 is an ovoid and complex chondrule (590×720 µm). The chondrule is dominated by one large, blocky, olivine crystal (nearly the width of the chondrule) that is zoned from $Fo_{93}$ in the core to $Fo_{82}$ along fractures and at the rim. The margin of the olivine crystal is highly scalloped and corroded, and external to it is a discontinuous outer zone consisting of untwinned enstatite crystals ($En_{92}$) that locally enclose round blebs of Fe-rich olivine. In the core of the olivine crystal, and at the center of the chondrule, is an irregular oblong area ~470 µm across consisting of enstatite, plagioclase ($An_{78-85}$), diopside, rounded Fe-rich olivine grains, and minor nepheline that replaces plagioclase. The core may be a trapped relict fragment, but it might also be a re-entrant of the enstatite rim zone that projects into the olivine from the third dimension. *CS* ("relict" core only and uncertain): olivine/diopside, enstatite, plagioclase. Chainpur 1251-16-3 is a round barred olivine chondrule (diameter ≈ 475 µm), with Mg-rich olivine ($Fo_{96-99}$) set in clear, pink, isotropic glass (23-25% $Al_2O_3$, 2-5% $Na_2O$, 1.5-2% FeO). A 25-50 µm rim enclosing the chondrule consists of coarse olivine, parts of which are in optical continuity with the internal bars. On one edge of the chondrule is part of a sulfide nodule. Fine-grained sulfides rim this part of the chondrule. A few small skeletal pyroxene crystals up to ~40 µm across occur in the glass on one side of the chondrule. They consist of pigeonite cores rimmed by aluminous diopside; very thin exsolution lamellae (enstatite?) are present in the pigeonite. *CS*: olivine, pyroxene, glass. Chainpur 5674-3b-1 is a rounded, somewhat lumpy, compound chondrule (diameter ≈ 850 µm). Most of the object has a porphyritic-olivine texture (+ metal + sulfide), with small interstitial patches of clear, isotropic glass. Enclosed within this larger region is a hemispherical fragment of a barred olivine chondrule, about 400 µm in original diameter. This barred region contains a single set of olivine bars (20-25 µm thick), in optical continuity with an olivine rim of about the same thickness. Interstitial to the olivine bars is clear, pink isotropic glass (30-32% $Al_2O_3$, 4-8% $Na_2O$, 1-2% FeO, <<1% CaO). Unlike the enclosing porphyritic portion of the chondrule, the barred inclusion is nearly metal- and sulfide-free. In both parts of the compound chondrule, the olivine is mostly very Mg-rich ($Fo_{98-99}$), with only very thin crystal margins and areas bordering fractures that are more Fe-rich ($Fo_{91}$).

Two of four chondrules contain clear evidence of $^{26}Mg^*$ (Table 1). In Semarkona 4128-3-2, the $(^{26}Al/^{27}Al)_o$ inferred from olivine, pyroxene, and plagioclase is within a factor of two of that in CAIs (Table 1), and is a factor of ~2.5 higher than the highest ratios inferred for other Al-rich chondrules

[1,2]. In Chainpur 1251-16-3, olivine and glass give $(^{26}Al/^{27}Al)_o = (4.3\pm1.5)\times10^{-6}$. However, the skeletal pyroxene (Al/Mg = 0.11) also has a 2.7±1.1‰ excess of $^{26}$Mg*. A possible explanation is that Mg from the glass was incorporated into pyroxene as the enstatite exsolved from pigeonite after $^{26}$Al had decayed. The glass-bearing chondrule, Chainpur 5674-3b-1, has a hint of $^{26}$Mg*, but the complex chondrule, Chainpur 1251-16-2, has no resolvable $^{26}$Mg* (Table 1).

Our new results bring to 5 the number of CAIs from UOCs in which Al-Mg isotopic measurements have been made. Four of these yield $(^{26}Al/^{27}Al)_o \approx 5\times10^{-5}$ [1, 2, this study] the same as in unaltered CAIs in carbonaceous chondrites [*cf.* 3]. The fifth UOC CAI, from Dhajala, is a FUN inclusion and has a much lower $(^{26}Al/^{27}Al)_o$ [4]. Thus, UOC CAIs appear to have formed either from reservoirs isotopically similar to, or the same reservoirs as, carbonaceous-chondrite CAIs, and the two groups of CAIs must have formed at about the same time. The presence of radiogenic $^{26}$Mg* at $(^{26}Al/^{27}Al)_o \approx 5\times10^{-5}$ in volatile-rich, secondary sodalite in Semarkona 4128-3-1 indicates that low-temperature alteration of CAIs began almost immediately after CAI formation.

A major goal of this study is to understand the timing of chondrule and CAI formation. Previously, we reported two UOC chondrules with $(^{26}Al/^{27}Al)_o = (8\text{-}9)\times10^{-6}$ [1,2], and, in agreement with previous workers [5,6], we also reported several chondrules with no evidence of $^{26}$Al. The data were interpreted to indicate that chondrule formation began ~2 Ma after CAIs formed and continued for several Ma, assuming an initially homogeneous nebula. The new data for Semarkona chondrule 4128-3-2 (Table 1) change this picture. If the nebula were homogeneous in $^{26}Al/^{27}Al$, then Semarkona 4128-3-2 formed <1 Ma after the earliest CAIs. Chainpur chondrules 1251-16-3 and 5674-3b-1 (Table 1), and 1251-3-1 [2] all contain $^{26}$Mg*, with $(^{26}Al/^{27}Al)_o$ values of $9\times10^{-7}$ to $9\times10^{-6}$. Chondrites are collections of diverse objects with different pre-accretionary histories. The Al-Mg systematics of chondrules in meteorites that have experienced little or no parent-body metamorphism probably reflect nebular history. The range of $(^{26}Al/^{27}Al)_o$ exhibited by chondrules implies that chondrule formation took place over at least 4-5 Ma, implying an extended nebular lifetime. Individual meteorites seem to have acquired chondrules that formed throughout this period. If chondrules were produced in the nebula over such an extended period, they must have agglomerated into proto-planets tens to hundreds of meters in diameter on a time scale <<1 Ma to avoid being swept into the sun. These bodies were probably disrupted and reassembled many times before the final chondrite parent bodies formed.

The above discussion assumes that parent-body metamorphism has not affected Al-rich chondrules. Our new data may indicate a need to re-evaluate the role of metamorphism. Semarkona (LL3.0), which contains the chondrule with the highest inferred $(^{26}Al/^{27}Al)_o$, probably has not experienced temperatures above ~250°C [7,8], but Chainpur (LL3.4), which contains three glass-bearing chondrules with lower $(^{26}Al/^{27}Al)_o$, may have seen temperatures as high as 400°C [9]. The duration of this heating is not known, but fission-track studies suggest times of a few Ma [10]. New data for Mg diffusion in plagioclase [11] indicate that ~1.2 Ma at 600°C is sufficient to homogenize Mg in a 25 µm anorthite grain, while at 450°C, homogenization will take longer than the age of the solar system. Since Mg diffusion is probably more rapid in glass, we cannot completely rule out parent-body metamorphism as a cause of variations in $(^{26}Al/^{27}Al)_o$ in glass-bearing Chainpur chondrules. However, the experimental data indicate that anorthite-bearing chondrules with no $^{26}$Mg* in Chainpur [1,2] cannot be attributed to parent-body metamorphism. This intepretation is supported by the presence of $^{26}$Mg* in an anorthite-bearing chondrule from Inman, also LL3.4. Thus, the range of $(^{26}Al/^{27}Al)_o$ in anorthite-bearing chondrules in primitive chondrites (~0 to $2.5\times10^{-5}$) most likely implies an extended period of chondrule formation.

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| Name | Mineralogy | $(Al/Mg)_{max}$ | $\delta\,^{26}Mg^*_{max} \pm 2\sigma$ | $(^{26}Al/^{27}Al)_o$ $(\times 10^{-5}) \pm 2\sigma$ | Time from CAI (Ma) |
|---|---|---|---|---|---|
| Semarkona 4128-3-1 | melilite-px | 16 | 7.2 ± 2.9 | 6.4 ± 2.8 | ~0 |
| | sodalite-px | 18 | 9.1 ± 3.8 | 6.5 ± 1.5 | ~0 |
| Moorabie 6302-2-1 | hibonite-spinel | 36 | 13.8 ± 1.8 | 4.9 ± 0.7 | ~0 |
| Semarkona 4128-3-2 | plag-sp-ol-px-gls | 36 | 5.2 ± 1.2 | 2.4 ± 0.6 | ~0.7 |
| Chainpur 1251-16-3 | ol-px-glass | 127 | 3.7 ± 1.4 | 0.43 ± 0.15 | ~3 |
| Chainpur 5674-3b-1 | ol-glass | 650 | 2.8 ± 3.9 | 0.09 ± 0.07 | ~4.5 |
| Chainpur 1251-16-2 | plag-px-ol | 175 | 2.2 ± 3.1 | ≤ 0.32 | ≥ 2.5 |